CP, T, and CPT tests at CPLEAR

Ludwig Tauscher
Basel University
and
ETH-Zurich

Introduction

Since the discovery of the antiproton large amounts of them have been produced,
- but only few have been used to study the antiproton itself.
- Instead, they were interesting because of **their negative** charge (make out of a single ring accelerator a pp_{bar} collider),
- or they were used as **fuel** to be burned with nucleons to generate new mesons or specific particle states.

With the advent of **antiproton accumulation** techniques in 1978 (*Rubbia, Van der Meer*) large amounts of antiprotons (10^9 p_{bar}s/hr) became available for further acceleration ($Spp_{bar}S$ collider) OR deceleration (LEAR, *D. Moehl, P. Lefevre*).

This talk: use a flux of 10^6 $\bar{p}$/s from LEAR to produce a particular final state from $p\bar{p}$ annihilation containing neutral kaons with tagged strangeness.

CPLEAR strangeness tagging

Stop $\bar{p}$ in a hydrogen gas target
$\Rightarrow$ formation of atomic $p\bar{p}$ -state (B = S = 0) at rest
$\Rightarrow$ annihilation (strong process), conservation of symmetries.

Select equally abundant final states $K^{-}_{s\bar{u}} K^{0}_{\bar{s}d} \pi^{+}$
$K^{+}_{\bar{s}u} \bar{K}^{0}_{s\bar{d}} \pi^{-}$

use $K^{\pm}$ for tagging the strangeness of the neutral Kaon.

For the first time study (with high statistics) the decay properties of particles and their antiparticles and compare them.
Any particle-antiparticle difference signals violation of symmetry

Outline

1. Recall some of the phenomenology of neutral Kaons
2. Define the measurables
3. Present the experiment
4. Discuss results

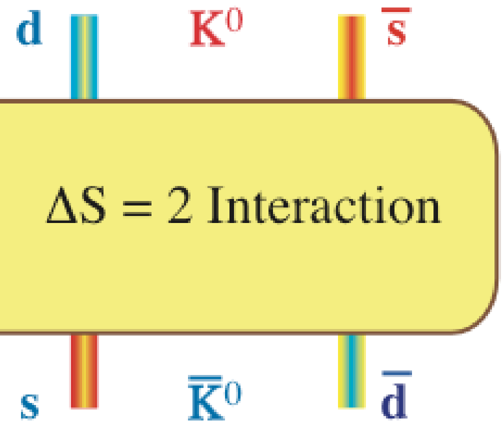
Neutral Kaons with fixed strangeness

Neutral kaons: $\boxed{K^0\left(\bar{s}d\right)_{S=+1},\ \bar{K}^0\left(s\bar{d}\right)_{S=-1}}$

Quarks are unstable: $|\Delta Q|_{\text{"up"}\leftrightarrow\text{"down"}} = 1$

Mixing:

phenomenological



"box"

virtual decay

⇒ Neutral kaons with fixed strangeness do not exist in nature

Neutral Kaons with definite CP

If transmutation rates $\bar{K}^0 \to K^0 = K^0 \to \bar{K}^0$

Then the neutral kaons have strangeness $S = \pm 1$ with equal probability:

CP-Eigenstates: $\boxed{K_{"S"} = \sqrt{\tfrac{1}{2}}\left(K^0 + \bar{K}^0\right)_{CP=+1} \qquad K_{"L"} = \sqrt{\tfrac{1}{2}}\left(K^0 - \bar{K}^0\right)_{CP=-1}}$

The **$\Delta S = 2$ *mixing interaction*** leads to a **mass splitting**:

$$m_{K_{"L"}} - m_{K_{"S"}} = \Delta m = 3.5 \times 10^{-6}\ [\mathrm{eV}] \Rightarrow \frac{\Delta m}{m_K} = 7 \times 10^{-15}$$

The ***CP-selection*** leads to the major hadronic **decays**:

$\mathbf{K_{"S"}} \to \pi\pi(\approx 100\%),\ \pi\ell\nu$ $\qquad \gamma_{"S"} \approx 7.5\times10^{-6}[\mathrm{eV}]$

$\mathbf{K_{"L"}} \to \pi\pi\pi(\approx 33.7\%),\ \pi\ell\nu(\approx 66\%)$ $\qquad \gamma_{"L"} \approx 1.3\times10^{-8}[\mathrm{eV}]$

(**lifetime difference** mainly due to **phase space**) $\qquad \gamma_{\pi\ell\nu} \approx 0.9\times10^{-8}[\mathrm{eV}]$

Real Neutral Kaons

CP-violation (*Christenson, Cronin, Fitch and Turlay*, P.R.L. 13, 138 (1964))

K_L decays also into $\pi\pi$, i.e. K_L must contain a small fraction of K_S

Reason 1: Neutral Kaons "more often" K^0 than $\bar{K}^0$, i.e.

transmutation rate $\bar{K}^0 \to K^0$ larger than $K^0 \to \bar{K}^0$ **(T-reversal violation)**

$$K_S = \sqrt{\tfrac{1}{2}}\left((1+\varepsilon)K^0 + (1-\varepsilon)\bar{K}^0\right) \qquad K_L = \sqrt{\tfrac{1}{2}}\left((1+\varepsilon)K^0 - (1-\varepsilon)\bar{K}^0\right)$$

ε is a small number

Reason 2: K_S are "more often" K^0 than $\bar{K}^0$, while

K_L are "more often" $\bar{K}^0$ than K^0 **(CPT violation)**

$$K_S = \sqrt{\tfrac{1}{2}}\left((1+\delta)K^0 + (1-\delta)\bar{K}^0\right) \qquad K_L = \sqrt{\tfrac{1}{2}}\left((1-\delta)K^0 - (1+\delta)\bar{K}^0\right)$$

δ is a small number

Time evolution (*Wigner Weisskopf*)

General Neutral Kaon state: $|\Psi(t)\rangle = a(t)|K^0\rangle + b(t)|\bar{K}^0\rangle$

Schroedinger equation: $$i\frac{\partial}{\partial t}\begin{pmatrix} a(t) \\ b(t) \end{pmatrix} = \mathrm{H}\begin{pmatrix} a(t) \\ b(t) \end{pmatrix}$$

M and Γ hermitian

$$\boxed{\mathrm{H} = \begin{pmatrix} \mathrm{M}_{K^0K^0} = \mathrm{m}_{K^0} & \mathrm{M}_{K^0\bar{K}^0} \\ \mathrm{M}_{\bar{K}^0K^0} & \mathrm{M}_{\bar{K}^0\bar{K}^0} = \mathrm{m}_{\bar{K}^0} \end{pmatrix} - \frac{i}{2}\begin{pmatrix} \Gamma_{K^0K^0} = \gamma_{K^0} & \Gamma_{K^0\bar{K}^0} \\ \Gamma_{\bar{K}^0K^0} & \Gamma_{\bar{K}^0\bar{K}^0} = \gamma_{\bar{K}^0} \end{pmatrix}}$$

Eigenvalues
(measured quantities)

$$\mathrm{m}_{K_L\,K_S} = \tfrac{1}{2}\left(\mathrm{M}_{K^0K^0} + \mathrm{M}_{\bar{K}^0\bar{K}^0}\right) \mp \mathrm{Re}\,\mathrm{M}_{K^0\bar{K}^0} \qquad \Delta \mathrm{m}_{L-S} = -2\,\mathrm{Re}\,\mathrm{M}_{K^0\bar{K}^0}$$

$$\gamma_{K_L\,K_S} = \tfrac{1}{2}\left(\Gamma_{K^0K^0} + \Gamma_{\bar{K}^0\bar{K}^0}\right) \mp \mathrm{Re}\,\Gamma_{K^0\bar{K}^0} \qquad \Delta \gamma_{L-S} = -2\,\mathrm{Re}\,\Gamma_{K^0\bar{K}^0}$$

The physics of mixing and symmetry violations resides in the matrix elements of M and Γ

Phenomenological symmetry violation parameters

T-violation

$$\varepsilon = \frac{\mathrm{Im}M_{K^0\bar{K}^0} - \frac{i}{2}\mathrm{Im}\Gamma_{K^0\bar{K}^0}}{\sqrt{\Delta m^2 + |\Delta\gamma/2|^2}} e^{i\phi_{SW}}$$

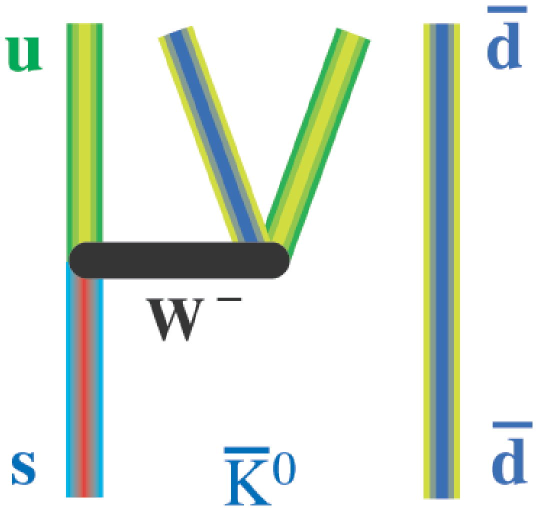
CPT-violation

$$\delta = \frac{i}{2}\frac{\left[m_{K^0} - m_{\bar{K}^0}\right] - \frac{i}{2}\left[\gamma_{K^0} - \gamma_{\bar{K}^0}\right]}{\sqrt{\Delta m^2 + |\Delta\gamma/2|^2}} e^{i\phi_{SW}}$$

"Super weak phase": $\phi_{SW} = \mathrm{atan}\left(\frac{2\Delta m}{|\Delta\Gamma|}\right) \approx 43^o$

Superweak model (*Wolfenstein*): $\Phi_\varepsilon = \Phi_{SW}$ $\mathrm{Im}\Gamma_{K^0\bar{K}^0} = 0$

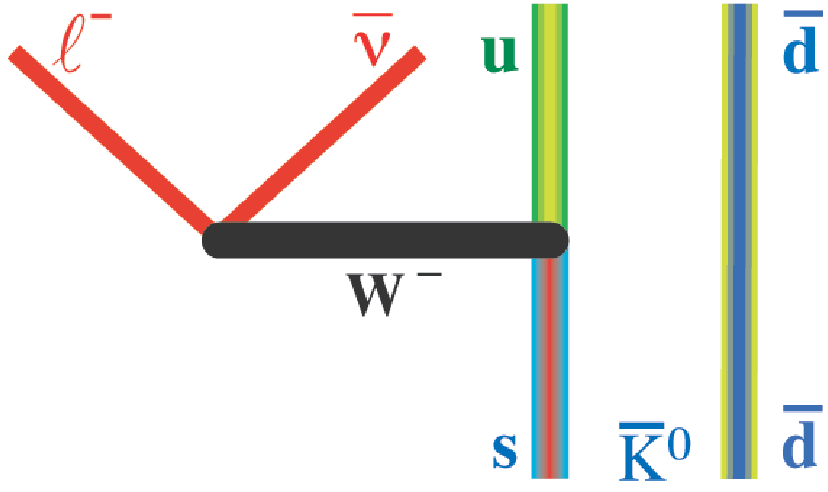
Standard decays of neutral kaons



Hadronic decay

Not flavor specific

CP selection



Semileptonic decay

flavor specific

s quark (S=-1) $\Rightarrow$ ℓ^-

$\bar{s}$ quark (S=+1) $\Rightarrow$ ℓ^+

($\Delta S = \Delta Q$ - rule)

Measurable quantities

Strangeness tagging

$$\begin{pmatrix} |K^0\rangle \\ |\bar{K}^0\rangle \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1-\varepsilon+\delta & 1-\varepsilon-\delta \\ 1+\varepsilon-\delta & -1-\varepsilon-\delta \end{pmatrix} \begin{pmatrix} |K_S\rangle \\ |K_L\rangle \end{pmatrix} \qquad \Psi_{S,L} \propto e^{-i\left(m_{S,L}-\frac{i}{2}\gamma_{S,L}\right)t}$$

Decay amplitudes

$$A+B = \left\langle f_{I,\ell^\pm} \middle| H \middle| K^0 \right\rangle, \qquad -A^*+B^* = \left\langle f_{I,\ell^\pm} \middle| H \middle| \bar{K}^0 \right\rangle$$

***A*: CPT conserving**
***B*: CPT violating**

$$a_S^f = \left|a_S^f\right| e^{i\Phi_S^f} = \left\langle f \middle| H \middle| K_S \right\rangle, \qquad a_L^f = \left|a_L^f\right| e^{i\Phi_L^f} = \left\langle f \middle| H \middle| K_L \right\rangle$$

Decay rates

$$R_{\substack{K^0 \\ \bar{K}^0} \to f} = \left.\begin{matrix} R_f(t) \\ \bar{R}_f(t) \end{matrix}\right\} = \frac{1 \mp 2\,\mathrm{Re}\,\varepsilon}{2} \left\{ \begin{matrix} \left(1 \mp 2\mathrm{Re}\delta\right)\left|a_S^f\right|^2 e^{-\gamma_S t} + \left(1 \pm 2\mathrm{Re}\delta\right)\left|a_L^f\right|^2 e^{-\gamma_L t} \\ \pm 2\left|a_S^f\right|\left|a_L^f\right| e^{-\frac{\gamma_S+\gamma_L}{2}t} \cos\left(\Delta m t - \Phi_f\right) \end{matrix} \right\}$$

Asymmetries

$$A_f(t) = \frac{\bar{R}_f(t) - R_f(t)}{\bar{R}_f(t) + R_f(t)}$$

Many systematic errors cancel

ππ rates and asymmetries

Decay rate

$$\left.\begin{matrix} R_{\pi\pi}(t) \\ \bar{R}_{\pi\pi}(t) \end{matrix}\right\} = \frac{\Gamma_{\pi\pi}}{2}\left(1 \mp 2\,\mathrm{Re}(\varepsilon-\delta)\right)\left\{e^{-\gamma_S t} + |\eta_{\pi\pi}|^2 e^{-\gamma_L t} \pm \boxed{2|\eta_{\pi\pi}| e^{-\frac{\gamma_S+\gamma_L}{2}t}\cos\left(\Delta m t - \Phi_{\pi\pi}\right)}\right\}$$

$$\eta_{\pi\pi} = \frac{a_L^{\pi\pi}}{a_S^{\pi\pi}} = |\eta_{\pi\pi}| e^{i\Phi_{\pi\pi}}$$

asymmetry

$$A_{\pi\pi}(t) = \frac{\bar{R}_{\pi\pi}(t) - \alpha_{\pi\pi} R_{\pi\pi}(t)}{\bar{R}_{\pi\pi}(t) + \alpha_{\pi\pi} R_{\pi\pi}(t)}, \qquad \alpha_{\pi\pi} = 1 + 4\,\mathrm{Re}(\varepsilon-\delta)$$

Singles out interference term

$$A_{\pi\pi}(t) = -2\frac{|\eta_{\pi\pi}| e^{-\frac{\gamma_S+\gamma_L}{2}t}\cos\left(\Delta m t - \Phi_{\pi\pi}\right)}{e^{-\gamma_S t} + |\eta_{\pi\pi}|^2 e^{-\gamma_L t}}$$

$$\eta_{+-} = \varepsilon - \delta + \left(i\frac{\mathrm{Im}\,A_0}{\mathrm{Re}\,A_0} + \frac{\mathrm{Re}\,B_0}{\mathrm{Re}\,A_0}\right) + \varepsilon'$$

$$\eta_{00} = \varepsilon - \delta + \left(i\frac{\mathrm{Im}\,A_0}{\mathrm{Re}\,A_0} + \frac{\mathrm{Re}\,B_0}{\mathrm{Re}\,A_0}\right) - 2\varepsilon'$$

$$\varepsilon' = \frac{e^{i(\delta_2-\delta_0)}}{\sqrt{2}}\frac{\mathrm{Re}\,A_2}{\mathrm{Re}\,A_0}\left[i\left(\frac{\mathrm{Im}\,A_2}{\mathrm{Re}\,A_2} + \frac{\mathrm{Im}\,A_0}{\mathrm{Re}\,A_0}\right) + \left(\boxed{\frac{\mathrm{Re}\,B_2}{\mathrm{Re}\,A_2}} - \boxed{\frac{\mathrm{Re}\,B_0}{\mathrm{Re}\,A_0}}\right)\right]$$

The factor $\alpha_{\pi\pi}$ will later be absorbed in a relative K^0 - $\bar{K}^0$ normalization (CPLEAR normalization)

semileptonic amplitudes and rates

decay amplitudes,
with respect to strangeness at decay

$$\Delta S = \Delta Q: \quad a_f + b_f = \langle e^+\pi^-\nu | H | K^0 \rangle, \quad -a_f^* + b_f^* = \langle e^-\pi^+\bar{\nu} | H | \bar{K}^0 \rangle$$

$$\Delta S \neq \Delta Q: \quad a_g + b_g = \langle e^-\pi^+\bar{\nu} | H | K^0 \rangle, \quad -a_g^* + b_g^* = \langle e^+\pi^-\nu | H | \bar{K}^0 \rangle$$

Symmetry violating parameters $x_+ = \frac{a_g}{a_f}\ (\Delta S \neq \Delta Q)$, $y = \frac{b_f}{a_f}(\Delta S{=}\Delta Q, \cancel{\text{CPT}})$, $x_- = -\frac{b_g^*}{a_f}\ (\Delta S \neq \Delta Q, \cancel{\text{CPT}})$

Decay rates (change of strangeness between creation and decay (blue), and no change (red))

$$\begin{pmatrix} R^-(t) \\ \bar{R}^+(t) \\ R^+(t) \\ \bar{R}^-(t) \end{pmatrix}^{\text{change of S}}_{\text{no change of S}} = \frac{|a_f|^2}{2} e^{-\frac{\gamma_S+\gamma_L}{2}t} \left[\cosh\left(\tfrac{\Delta\gamma}{2}t\right)\begin{pmatrix}1\\1\\1\\1\end{pmatrix} + \cos(\Delta m t)\begin{pmatrix}-1\\-1\\1\\1\end{pmatrix} \right.$$

normal decays with self-interference

$$+\left(\cosh\left(\tfrac{\Delta\gamma}{2}t\right) + \cos(\Delta m t)\begin{pmatrix}-1&0&0&0\\0&-1&0&0\\0&0&1&0\\0&0&0&1\end{pmatrix}\right)\left[\begin{pmatrix}-4\,\mathrm{Re}\,\varepsilon + 2\,\mathrm{Re}\,y\\ +4\,\mathrm{Re}\,\varepsilon - 2\,\mathrm{Re}\,y\\ -2\,\mathrm{Re}\,y\\ +2\,\mathrm{Re}\,y\end{pmatrix}\right.$$

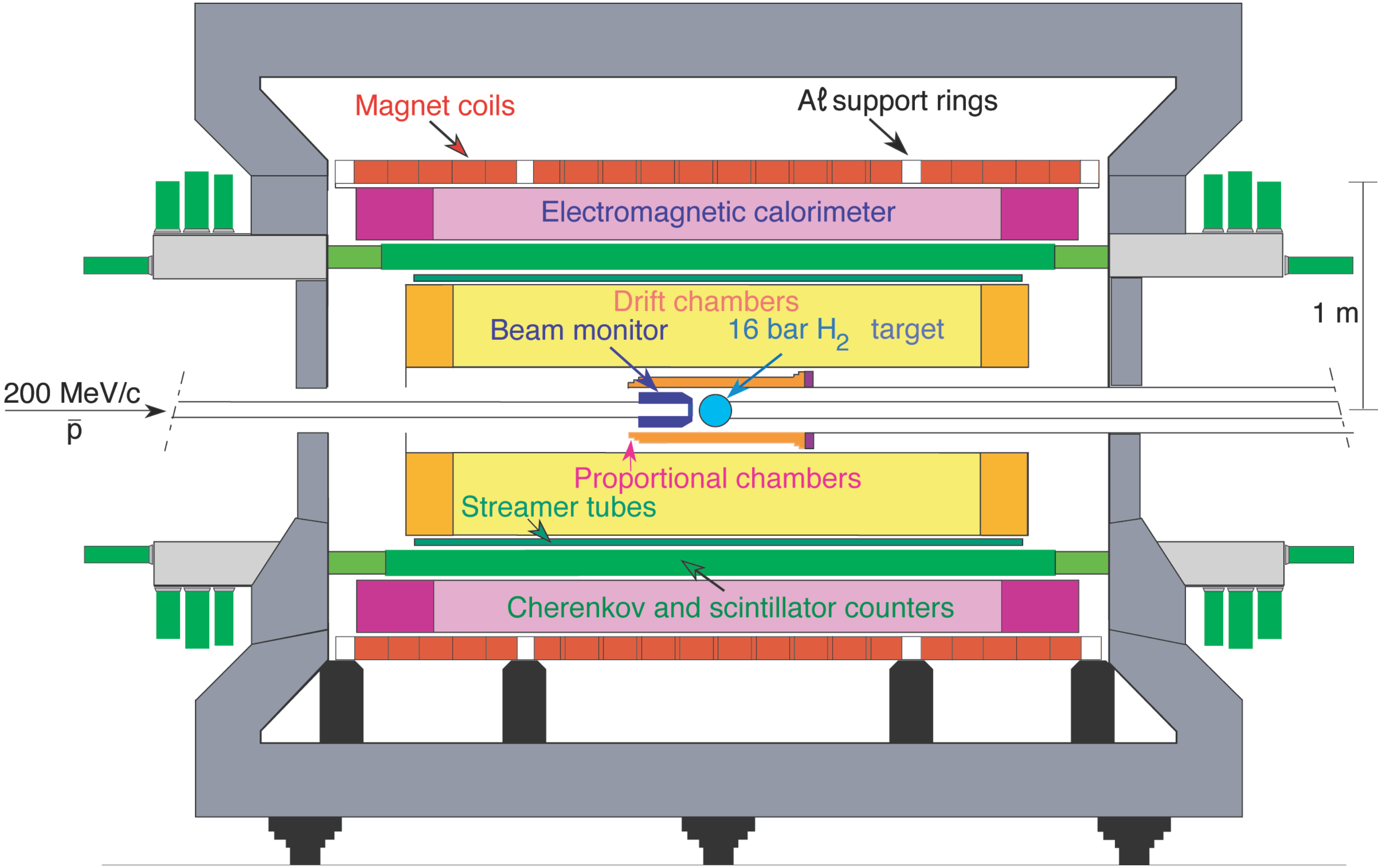
CP-violation in mixing
CPT violation in $\Delta S = \Delta Q$ decays

$$\left. -2\sinh\left(\tfrac{\Delta\gamma}{2}t\right)\begin{pmatrix}\mathrm{Re}(x_+ - x_-)\\ \mathrm{Re}(x_+ + x_-)\\ +2\,\mathrm{Re}\,\delta + \mathrm{Re}(x_+ + x_-)\\ -2\,\mathrm{Re}\,\delta + \mathrm{Re}(x_+ - x_-)\end{pmatrix} - 2\sin(\Delta m t)\begin{pmatrix}\mathrm{Im}(x_+ - x_-)\\ -\mathrm{Im}(x_+ + x_-)\\ +2\,\mathrm{Im}\,\delta + \mathrm{Im}(x_+ + x_-)\\ -2\,\mathrm{Im}\,\delta - \mathrm{Im}(x_+ - x_-)\end{pmatrix}\right]\right]$$

CPT violation in mixing
$\Delta S \neq \Delta Q$
CP and CPT violation in $\Delta S \neq \Delta Q$ decays

The CPLEAR detector

0.44 T



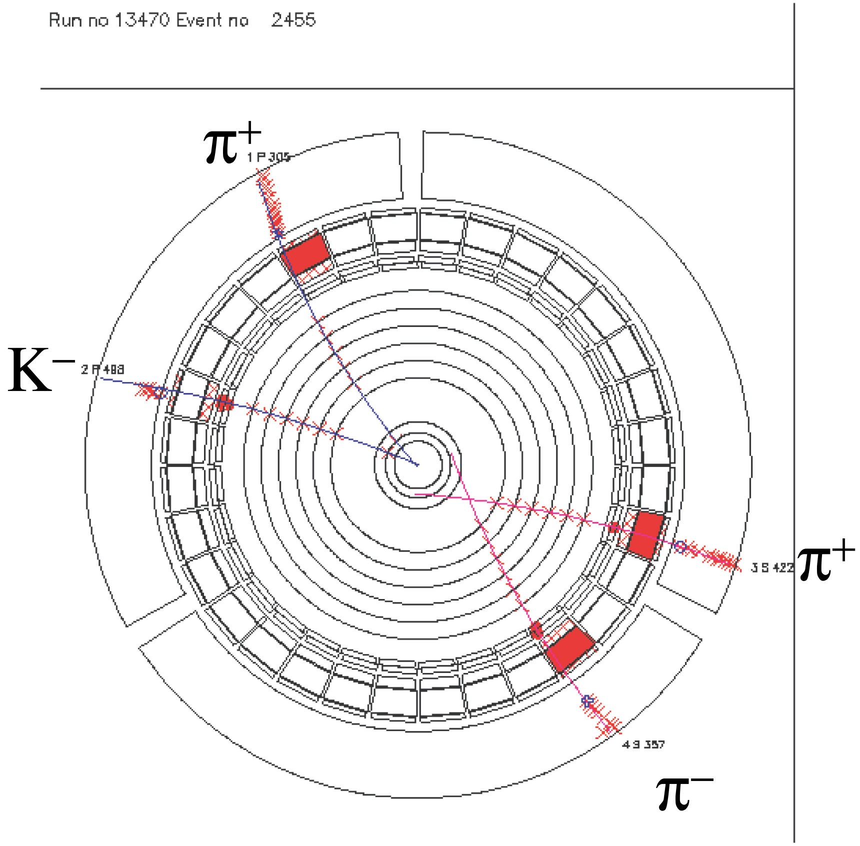
A typical ππ event

$\sigma m_{\pi+\pi-}$= 13.6 MeV/c^2

σm_{miss} = 82 MeV/c^2

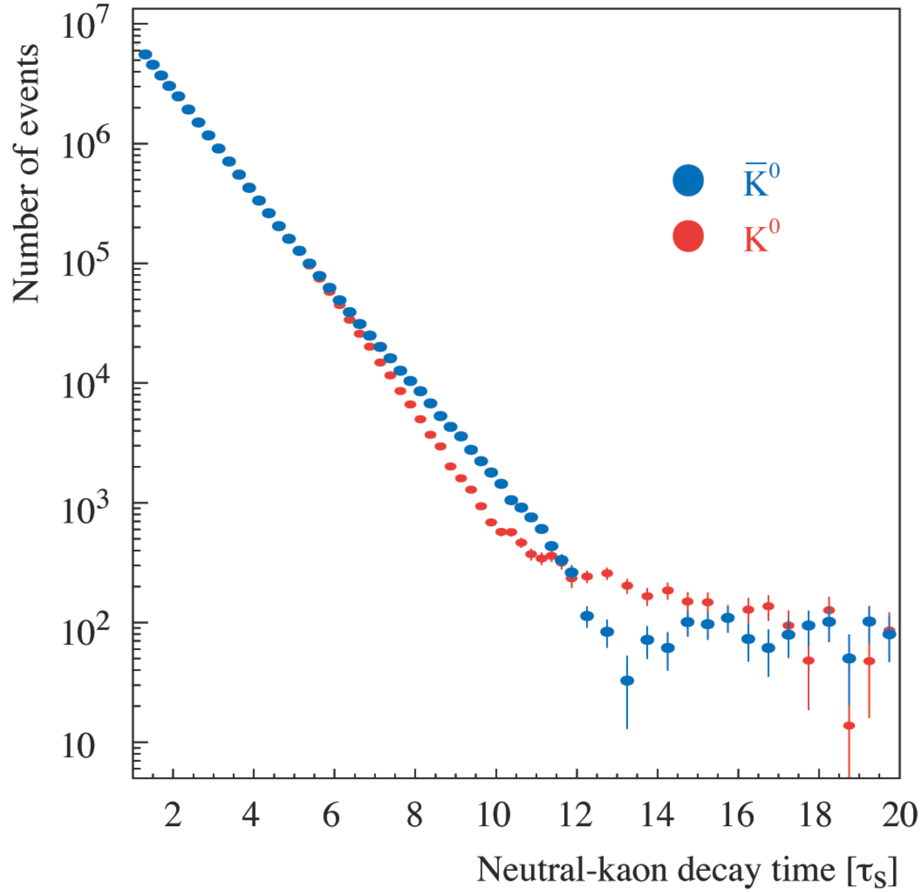
$\sigma\tau/\tau_S$ $\leq$ 10% for t<10τ_S

Altogether 10^{13} p_{bar}



Experimental decay rates of initial neutral kaons and antikaons into $\pi^+\pi^-$

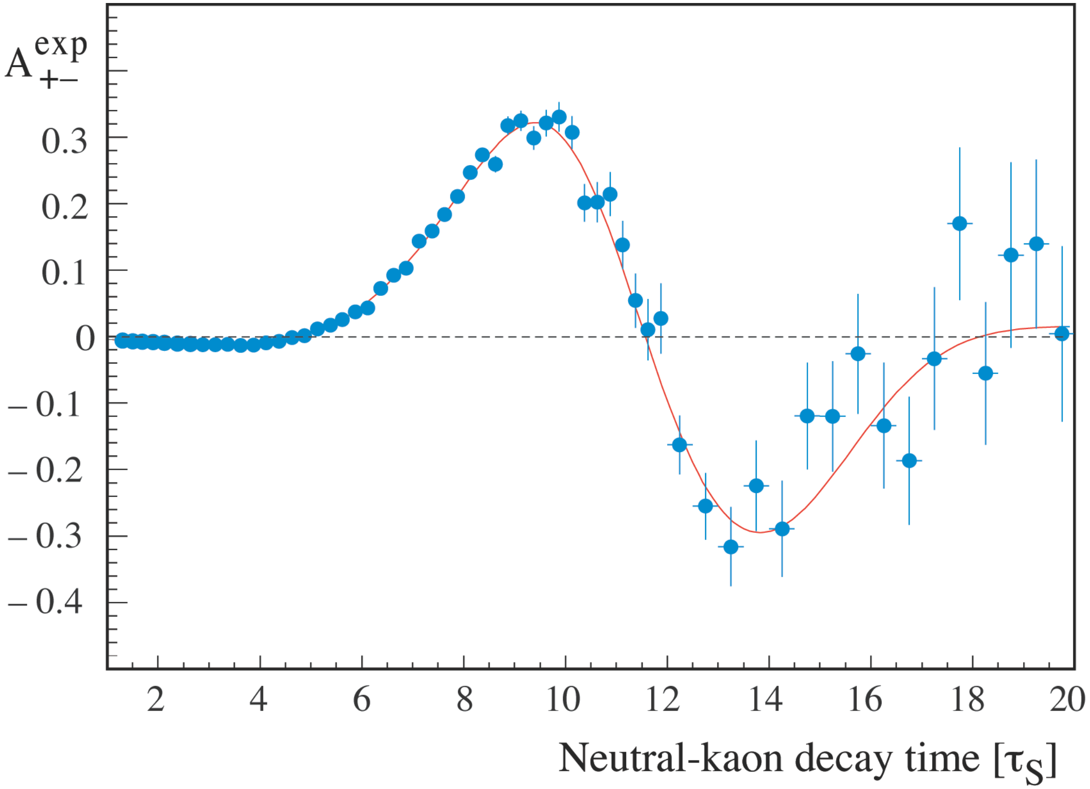
70×10^6 events



ππ asymmetry

$$A^{exp}_{+-}(t) = \frac{\bar{R}^{exp}_{+-}(t) - k R^{exp}_{+-}(t)}{\bar{R}^{exp}_{+-}(t) + k R^{exp}_{+-}(t)}$$

$$A^{th}_{+-}(t) = -2\frac{|\eta_{\pi\pi}| e^{-\frac{\gamma_S+\gamma_L}{2}t}\cos(\Delta m t - \Phi_{\pi\pi})}{e^{-\gamma_S t} + |\eta_{\pi\pi}|^2 e^{-\gamma_L t}}$$



$|\eta_{+-}| = (2.264 \pm 0.023_{stat} \pm 0.026_{syst} \pm 0.007_{\tau s})\times 10^{-3}$
$\Phi_{+-} = (43.19 \pm 0.53_{stat} \pm 0.28_{syst} \pm 0.42_{\Delta m})^{O}$
Ref.: Apostolakis et al, *Eur.Phys.J. C18 (2000) 41*

PDG2000
$|\eta_{+-}|_{average} = (2.277 \pm 0.017)\times 10^{-3}$
$\Phi_{+-} = (43.2 \pm 0.5)^{O}$ *(from fit, including* Δm *and* Φ_{SW}*)*

other hadronic decays

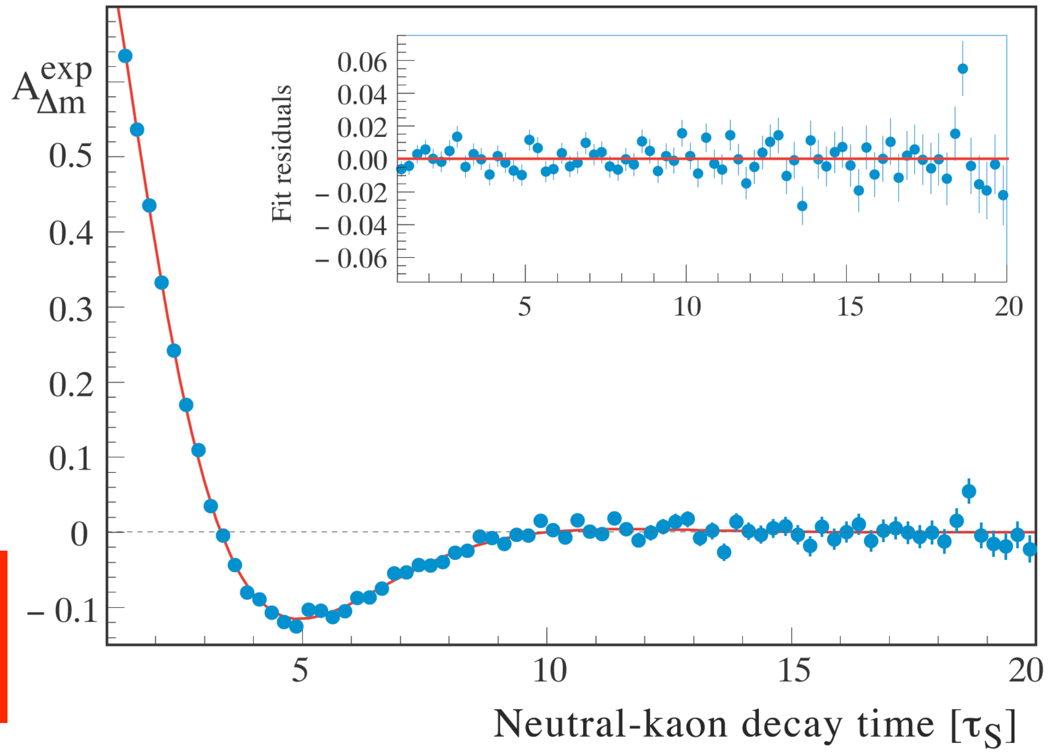
$\|\eta_{00}\| = (2.47 \pm 0.31_{stat} \pm 0.24_{syst})\times 10^{-3}$ $\Phi_{00} = (42.0 \pm 5.6_{stat} \pm 1.9_{syst})^{O}$ Ref.: Angelopoulos et al, *PL B420 (1998) 191*	***PDG2000*** $\|\eta_{00}\|_{average} = (2.12 \pm 0.11)\times 10^{-3}$ $\Phi_{00} = (43.2 \pm 1.0)^{O}$ *(from fit, including* Δm *and* Φ_{SW}*)*
$Re(\eta_{+-0}) = (-2 \pm 7_{stat}\ [^{+4}{}_{-1}]_{syst})\times 10^{-3}$ $Im(\eta_{+-0}) = (-2 \pm 9_{stat}\ [^{+2}{}_{-1}]_{syst})\times 10^{-3}$ Ref.: Angelopoulos et al, *EPJ 5 (1998) 389*	***PDG2000*** ***no other independent entries***
$Re(\eta_{000}) = (180 \pm 140_{stat} \pm 60_{syst})\times 10^{-3}$ $Im(\eta_{000}) = (150 \pm 200_{stat} \pm 30_{syst})\times 10^{-3}$ Ref.: Angelopoulos et al, *PL B425 (1998) 391*	***PDG2000*** ***no other independent entries***

Semileptonic asymmetry Δm

1.3×10^6 semilept. events

$$A^{exp}_{\Delta m}(t)=\frac{\left(\bar{R}^-(t)+R^+(t)\right)-\left(\bar{R}^+(t)+R^-(t)\right)}{\left(\bar{R}^-(t)+R^+(t)\right)+\left(\bar{R}^+(t)+R^-(t)\right)}$$

$$A_{\Delta m}(t)=\frac{2\cos(\Delta m t)}{\cosh\left(\frac{1}{2}\Delta\gamma t\right)-2\,\mathrm{Re}\,x_+\sinh\left(\frac{1}{2}\Delta\gamma t\right)}$$



All semileptonic asymmetries measured for the first time

$\Delta m = (0.5295 \pm 0.0020_{stat} \pm 0.0003_{syst})\times10^{10}\hbar/s$
$\mathrm{Re}(x_+) = (-1.8 \pm 4.1_{stat} \pm 4.5_{syst})\times10^{-3}$
Ref.: Angelopoulos et al, *PL B444 (1998) 38*

PDG2000
$\Delta m_{average} = (0.5307 \pm 0.0015)\times10^{10}\hbar/s$
$\mathrm{Re}(x_+)_{average} = (-2 \pm 5)\times10^{-3}$

Semileptonic Time reversal asymmetry

***Kabir*-Theorem** *(Kabir, PR D2 (1970) 540)*

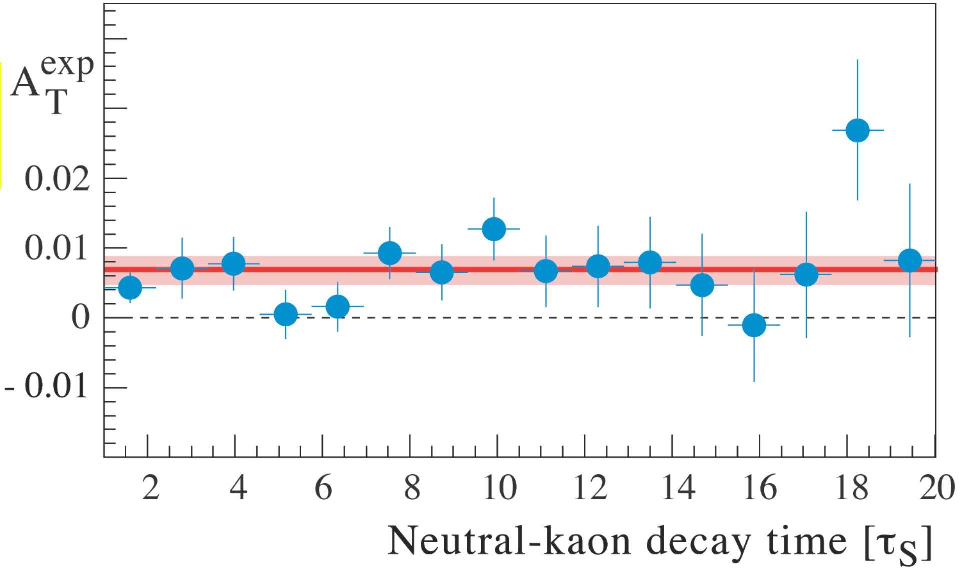
Time reversal invariance is violated, if the transformation rate $R_{\bar{K}^0_{t=0}\to K^0_t}(t) \neq R_{K^0_{t=0}\to \bar{K}^0_t}(t)$

Kabir-asymmetry:

$$\frac{R_{\bar{K}^0_{t=0}\to K^0_t} - R_{K^0_{t=0}\to \bar{K}^0_t}}{R_{\bar{K}^0_{t=0}\to K^0_t} + R_{K^0_{t=0}\to \bar{K}^0_t}}(t) \xrightarrow{\text{CPLEAR}} A_T^{exp}(t) = \frac{R_{\bar{K}^0_{t=0}\to e^+\pi^-\nu} - R_{K^0_{t=0}\to e^-\pi^+\bar{\nu}}}{R_{\bar{K}^0_{t=0}\to e^+\pi^-\nu} + R_{K^0_{t=0}\to e^-\pi^+\bar{\nu}}}(t) = \frac{\bar{R}^+ - R^-}{\bar{R}^+ + R^-}(t)$$

$\langle A_T \rangle_{average} = (6.6 \pm 1.3_{stat} \pm 1.0_{syst})\times 10^{-3}$

Ref.: Angelopoulos et al, *PL B444 (1998) 43*



$$A_T(t) = 4\,\mathrm{Re}(\varepsilon) - 2\,\mathrm{Re}(y + x_-)$$
$$+ 2\frac{\mathrm{Re}\,x_-\left(e^{-\frac{1}{2}\Delta\gamma t} - \cos(\Delta m t)\right) + \mathrm{Im}\,x_+ \sin(\Delta m t)}{\cosh\left(\frac{1}{2}\Delta\gamma t\right) - \cos(\Delta m t)}$$
$$\xrightarrow[t \gg \tau_S]{} 4\,\mathrm{Re}(\varepsilon) - 2\,\mathrm{Re}(y + x_-)$$

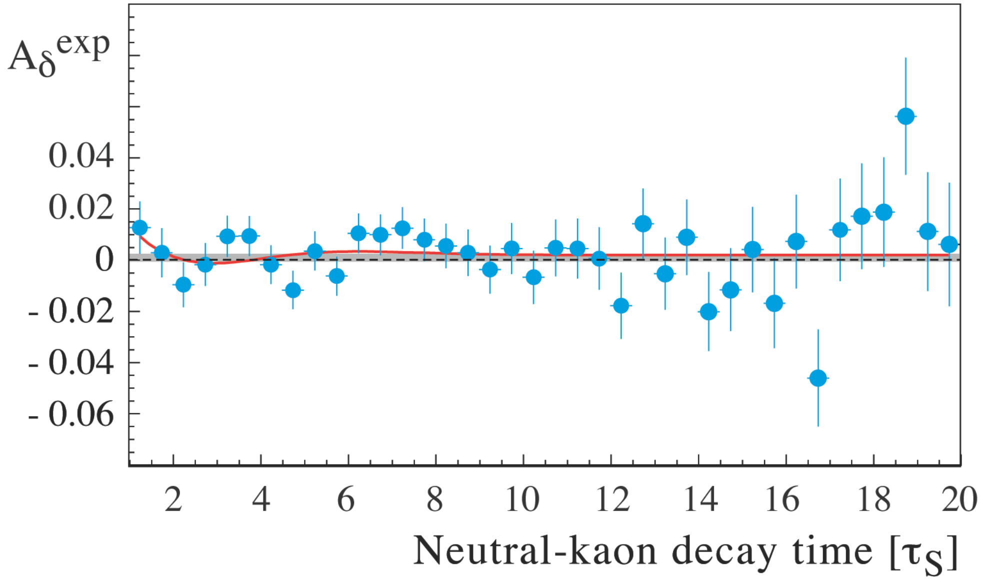
First ever measured T-reversal violation through rate comparison

Arrow of time: antikaons disappear faster than kaons (Reε >0)

Semileptonic CPT asymmetry

$$A_\delta^{exp}(t) = \left(\frac{\bar{R}^+ - \alpha_{\pi\pi} R^-}{\bar{R}^+ + \alpha_{\pi\pi} R^-} + \frac{\bar{R}^- - \alpha_{\pi\pi} R^+}{\bar{R}^- + \alpha_{\pi\pi} R^+} \right)(t)$$

$\langle A_{CPT} \rangle_{average} = (2.32 \pm 2.08_{stat} \pm 0.48_{syst}) \times 10^{-3}$
Ref.: Angelopoulos et al, *PL B444 (1998) 53*



$$A_\delta(t) = 4\,\mathrm{Re}(\delta)\left(1 + \frac{\sinh\left(\frac{1}{2}\Delta\gamma t\right)}{\cosh\left(\frac{1}{2}\Delta\gamma t\right) + \cos(\Delta m t)}\right) + \frac{4\,\mathrm{Im}(\delta)\sin(\Delta m t)}{\cosh\left(\frac{1}{2}\Delta\gamma t\right) + \cos(\Delta m t)}$$

$$-4\frac{\mathrm{Re}\,x_-\cos(\Delta m t)\sinh\left(\frac{1}{2}\Delta\gamma t\right) - \mathrm{Im}\,x_+\sin(\Delta m t)\cosh\left(\frac{1}{2}\Delta\gamma t\right)}{\cosh\left(\frac{1}{2}\Delta\gamma t\right)^2 - \cos(\Delta m t)^2}$$

$$\xrightarrow[t \gg \tau_S]{} 8\,\mathrm{Re}(\delta)$$

First ever measured Re(δ) without any constraint

Bell-Steinberger Unitarity Relation

Decaying neutral kaons must show up as decay final states

$$\left(i2\Delta\mathrm{m}+\Delta\gamma\right)\left(\mathrm{Re}\,\varepsilon-i\,\mathrm{Im}\,\delta\right)=\sum_{\text{f=all decay channels}}\left(\mathrm{A}_{\mathrm{S}}^{\mathrm{f}}\right)^{*}\left(\mathrm{A}_{\mathrm{L}}^{\mathrm{f}}\right)$$

Separate for real and imaginary part

$$\begin{pmatrix} 2\Delta\mathrm{m} & \gamma \\ -\gamma & 2\Delta\mathrm{m} \end{pmatrix}\begin{pmatrix} \mathrm{Im}\,\delta \\ \mathrm{Re}\,\varepsilon \end{pmatrix}=\begin{pmatrix} \mathrm{Re}\,\eta_{\pi\pi}\left|\mathrm{A}_{\mathrm{S}}^{\pi\pi}\right|^{2}+\mathrm{Re}\,\eta_{\pi\pi\pi}\left|\mathrm{A}_{\mathrm{L}}^{\pi\pi\pi}\right|^{2}-\mathrm{Re}\,y\,2\gamma_{L}\mathrm{B}_{\mathrm{L}}^{\pi\ell\nu} \\ \mathrm{Im}\,\eta_{\pi\pi}\left|\mathrm{A}_{\mathrm{S}}^{\pi\pi}\right|^{2}-\mathrm{Im}\,\eta_{\pi\pi\pi}\left|\mathrm{A}_{\mathrm{L}}^{\pi\pi\pi}\right|^{2}-\mathrm{Im}\,x_{+}\,2\gamma_{L}\mathrm{B}_{\mathrm{L}}^{\pi\ell\nu} \end{pmatrix}$$

The right hand side implies summation over all final states

Strategy:

Use all necessary entries on hadronic final states from CPLEAR and (if not available) from PDG1998

Fit semileptonic asymmetries using the unitarity equation as a constraint

Bell-Steinberger Unitarity, Results

Results (blue:Unitarity, red: semileptonic)

- o **$Re(\varepsilon) = (164.9 \pm 2.5)\times 10^{-5}$** — **$Im(\varepsilon)$: *not measurable***
- o **$Re(\delta) = (24 \pm 28)\times 10^{-5}$** — **$Im(\delta) = (2.4 \pm 5.0)\times 10^{-5}$**
- • **$Re(x_+) = (-1.8 \pm 6.1)\times 10^{-3}$** — **$Im(x_+) = (-2.0 \pm 2.7)\times 10^{-3}$**
- o **$Re(x_-) = (-0.5 \pm 3.0)\times 10^{-3}$** — **$Im(x_-)$: *not measurable***
- o **$Re(y) = (0.3 \pm 3.1)\times 10^{-3}$** — **$Im(y)$: *not measurable***
- o **$Re(y+x_-) = (-2 \pm 3)\times 10^{-4}$**

Ref.: Apostolakis et al, PL B456 (1999) 297

- • $Re(x_+)$ from Δm asymmetry

Global CPT Test

Mass- and decay-width differences for K and anti-K using the CPLEAR δ

$$\delta = i\frac{\left(m_{K^0}-m_{\bar{K}^0}\right)-\frac{i}{2}\left(\gamma_{K^0}-\gamma_{\bar{K}^0}\right)}{\sqrt{4\Delta m^2+\Delta\gamma^2}}e^{i\phi_{SW}}$$

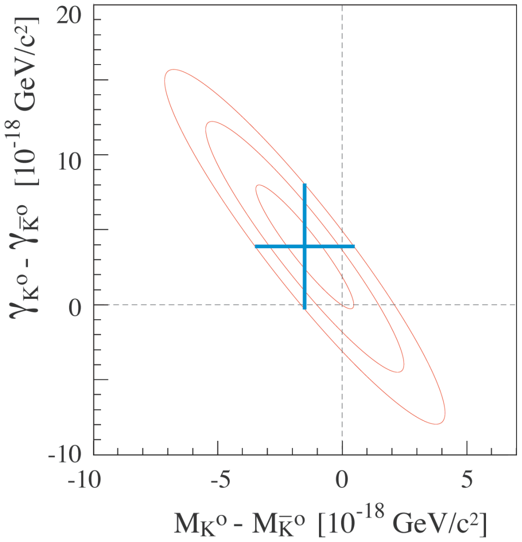
$$\boxed{\begin{pmatrix} m_{K^0}-m_{\bar{K}^0} \\ \gamma_{K^0}-\gamma_{\bar{K}^0}\end{pmatrix} = \sqrt{4\Delta m^2+\Delta\gamma^2}\begin{pmatrix} -\sin\phi_{SW} & \cos\phi_{SW} \\ 2\cos\phi_{SW} & 2\sin\phi_{SW}\end{pmatrix}\begin{pmatrix}\mathrm{Re}\,\delta \\ \mathrm{Im}\,\delta\end{pmatrix}}$$

Results

No assumptions except unitarity

$$\boxed{\begin{matrix} m_{K^0}-m_{\bar{K}^0} \\ \gamma_{K^0}-\gamma_{\bar{K}^0}\end{matrix} = \begin{matrix}(-1.5\pm 2.0)\times 10^{-18}\,[\mathrm{GeV}] \\ (\ 3.9\pm 4.2)\times 10^{-18}\,[\mathrm{GeV}]\end{matrix}}$$

Unique sensitivity on effects which violate CPT or look CPT violating



Summary

CPLEAR has used antiprotons for producing ***neutral kaons of tagged strangeness*** *(idea put forward by Gabathuler and Pavlopoulos)*

This allowed for ***particle-antiparticle comparisons*** *with large statistics*

All measurables in the neutral kaon system were determined with ***unprecedented precision*** *(except η_{00} and ε'),* ***many for the first time***

T-reversal violation *was measured* ***for the first time*** *and provided* ***arrow of time***

CPLEAR provided a ***CPT test of unprecedented precision*** *(thanks to the CPLEAR determination of η_{+-0} , η_{000} , $Re\delta$)*

In addition to what has been presented here CPLEAR has determined limits on ***CPT violating amplitudes in ππ decays****, studied* ***loss of quantum coherence*** *due to gravitation (CPT), equivalence principle, etc. etc.*

The neutral kaon system is a marvelous laboratory for expected or unexpected physics